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PHYSICAL, CHEMICAL AND POZZOLANIC PROPERTIES OF CANADIAN FLY ASHES

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SYNOPSIS

This report gives physical and chemical properties of fourteen Canadian fly ashes. The pozzolanic activity of the ashes seems to be related to the fineness rather than any other parameters measured; generally the finer the ash the higher the reactivity. All the fourteen ashes contain cenospheres. At least half of the ashes may be used as sources for cenospheres or lightweight fillers. Five of the ashes contain large amounts of magnetic particles and may be economical sources of magnetite.

INTRODUCTION

Raymond E. Davis and his associates appear to have coined the term "fly ash" in 1937. Following the pioneering studies by the U.S. Bureau of Reclamation for the Hungry Horse Dam, the use of fly ash for massive hydro-electric structures spread across the U.S.A., with ASTM issuing the first standard in 1954. In recent years because of the rapid rise in the cost of cement (current price being about $80/tonne), and concerns regarding the conservation of energy and resources, the use of fly ash and other supplementary cementing materials in ready-mixed concrete is receiving considerable attention. In 1982 Canada issued a National Standard CAN 3-A23.5-M82 entitled "Supplementary Cementing Materials and Their Use in Concrete Construction".

CANMET had initiated research in the area of supplementary cementing materials in the early 1970's and since then has published several comprehensive reports on the subject (1,2). This paper is a part of an overall study on Canadian fly ashes and their use in concrete, and covers an investigation on the physical, chemical and pozzolanic properties of fly ashes from 14 sources across the country.

SCOPE

The scope of the investigation was to determine:

(i) the various physical and chemical properties of fly ashes produced in different parts of the country,

(ii) the pozzolanic activity of the ashes, and to develop correlations, if any, between the physical and chemical properties and the pozzolanic activity of the ashes,

(iii) the ash fractions of different specific gravity, particularly the ash fraction lighter than water,

(iv) the magnetic fraction in the ashes.

Laboratory tests included elemental analysis, and other tests to determine specific gravity, specific surface area, fraction retained on 45 μm mesh, magnetic fraction, loss on ignition, fractionation of particles of different specific gravity, and pozzolanic activity index with portland cement, and with lime.

FLY ASH SOURCE

Fourteen fly ashes from different power plants shown in Figure 1, and listed in Table 1, were studied. The ash samples were received in 5-gallon pails or 45-gallon drums. Fly ashes No. 1 through 4 from Alberta and fly ash No. 6 from Saskatchewan are produced from subbituminous coal while fly ash No. 5, 7 and 8 from Saskatchewan are basically lignite ashes. Fly ashes No. 9 and 10 from Ontario and fly ashes No. 11 through 14 from the Maritime Provinces are basically bituminous fly ashes.

All the fly ashes are collected in electrostatic precipitators except fly ash No. 6 and 7 from Saskatchewan which are collected by

mechanical precipitators. The samples studied were obtained from the ash generally used for concrete work and/or structural fill in the respective provinces.

TEST PROCEDURES

Tests to determine chemical constituents were conducted by digesting the ash samples with nitric, hydrofluoric and perchloric acids. The ashes were fused with sodium carbonate for silica determination. All elemental analysis was done by Atomic Absorption Spectrometry.

Water soluble fraction was determined by mixing 10 g samples of ash in 500 ml of distilled water. The ash suspension was stirred for at least one hour, allowed to settle for 24 hours and restirred for one hour to ensure uniformity and complete solubility of water solubles.

Specific gravity and specific surface area of the ashes were determined by procedures described in ASTM C 188 and ASTM C 204 respectively.

Fractions of different specific gravity were determined by use of different liquids. These particular fluids namely water, chloroform and ethyl propyl alcohol of specific gravity 1.0, 1.47 and 0.78 respectively, were selected to evaluate fractions of different specific gravity in the ashes. A 10 g ash sample was mixed with the known liquid, and the floating particles were separated by decantation and filtration. Sediments from lighter fluids were tested for floating particles in the heavier liquids. Fraction lighter than one of the liquids in each ash was also determined by stirring a known mass of ash with each of the fluids separately and thus avoiding use of sediments from different fractionation tests using other liquids.

Tests to determine pozzolanic activity with cement, and with lime were conducted in accordance with ASTM C 311.

Magnetic fraction or fraction of ash that is attracted to a magnet was determined by suspending a known mass of ash in water in a test tube and placing the tube of suspension in a magnetic field. The data obtained include a large number of particles which were trapped between the magnetic particles. Attempts to wash the magnetically attracted particles and resuspend them and then subjecting the ash-water suspension to magnetic field did not produce satisfactory results in ashes containing high amounts of iron oxide.

TEST RESULTS

All the laboratory test data are presented in Tables 2 to 8. Selected data obtained from physical and chemical tests have been plotted to develop relevant correlations and are presented in Figures 2 through 11.

DISCUSSION OF TEST RESULTS

Sources of Fly Ashes

Available data presented in Figure 1 indicate that a large percentage of coal ash in Canada is produced in the Western Provinces. If the present trend of increased use of thermal coal for power generation continues, more and more fly ash is likely to be produced by the Western Provinces or from the coal originating from the Western Provinces. This explains why 8 of the 14 ash samples selected for study were from the Western Provinces. The 14 ashes selected also reflect the three basic types of coals used in Canada i.e. bituminous, sub-bituminous and lignite.

Fineness Variation

An examination of the data in Table 3 indicates that the specific surface area of the ashes collected by electrostatic precipitators is generally higher than the specific surface area of the ashes collected in mechanical precipitators (ashes No. 6 and 7). However, even some of the ashes collected in electrostatic precipitators had very low specific surface area. There does not seem to be a relationship between fineness, as measured by fraction retained on 45 μm, (Table 1) and either the coal type or the collection system. Apparently, the fineness of the pulverized coal and conditions of plant operations control the fly ash fineness. However, the mechanical precipitator Ash No. 7 was the coarsest ash as determined by the fraction retained on 45 μm mesh.

Pozzolanic Activity versus Other Parameters

Generally loss on ignition*, specific surface area, chemical composition and fineness are regarded as the parameters which have some effect on the pozzolanic activity of an ash. Some investigators have suggested that type and amount of glass (or amorphous matter), fineness and chemical composition of the glass, control the pozzolanic behaviour of an ash in that order (3,4). No test has yet been developed which allows accurate determination of glass in fly ash. As a result a combination of various parameters and their effects are used as a guide to evaluate ash activity.

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*Generally a measure of carbon content

Pozzolanic Activity versus (SiO_2 + Fe_2O_3 + Al_2O_3)

The amounts of oxides of silicon, iron and aluminum in an ash account for the bulk of ash. The data in Figure 2 and 3 indicate that ash reactivity with cement, and lime generally increased with increasing amounts of oxides of silicon, aluminum and iron. Majority of the glassy or amorphous matter in ash is composed of the oxides under consideration (5). Glass in fly ash particles reacts with lime to produce complex hydrates of calcium silicate, aluminate and ferro silicates (6). As the majority of the ashes are produced by burning pulverized coal in suspension-fired furnaces, it is likely that all the ashes have highly glassy particles. Therefore, the higher the amount of glass, containing oxides of silicon, aluminum, and iron the higher the activity.

Pozzolanic Activity versus CaO Content

Various investigators (7) have reported that generally the higher the amount of calcium oxide in the ash, the higher the ash reactivity. However, the foregoing statement always does not hold true. Joshi (8) from the study of synthetic and commercial fly ashes concluded that it is the form in which the calcium compound is present, not the calcium as reported in oxide form from the chemical analysis. It is also reported that many ashes which have high calcium compound, did not necessarily exhibit high pozzolanic activity and vice versa.

The data in Figures 4 and 5 indicate that there is a poor correlation between pozzolanic activity and CaO content of the ashes as determined from chemical analysis. For example, lignite ashes which have the highest amount of CaO show, with the exception of ash No. 5, relatively low reactivity with both portland cement and lime. It has been

reported that when the calcium is present in silicate or aluminate form, then only it imparts high reactivity to ash (9). Apparently ash No. 5 has calcium present in the form which allows high reactivity with lime in presence of water.

Pozzolanic Activity Versus Fineness

The effect of fineness on the pozzolanic activity is generally related by the fraction retained on 45 μm mesh sieve and by the specific surface area of fly ash (4,10). Both the tests and correlations have their drawbacks. However, many agencies prefer to specify both parameters for evaluating the ash activity rather than relying on one test.

Figures 6 and 7 present correlation between fraction retained on 45 μm and the activity index with cement, and with lime. The data suggest a general trend of decreasing activity in an ash with increasing fraction coarser than 45 μm mesh opening. The data on coarse fraction and activity indicate that ash No. 5 which contained the least amount of coarse fraction also was the most reactive.

The data in Figures 8 and 9 on fineness, as measured in terms of specific area, and activity indicate that generally the higher the surface area the higher the reactivity. However the correlation does not seem to be as specific as in Figures 6 and 7. Particularly the ash No. 4 has higher specific surface area than ash No. 5 but has lower pozzolanic activity as compared with the latter. Apparently the Blaine surface area test, which is really a measure of porosity of compacted ash sample, does not seem to give a realistic value of ash surface available for reaction with lime or cement. Some other test which could provide a more realistic value of available surface area for

reaction will go a long way in indicating ash reactivity.

Pozzolanic Activity Versus Water Soluble Content

The water soluble fraction of fly ash does not seem to be related to its pozzolanic activity. The data presented in Figure 10 and 11 does not suggest clearly a general trend of increasing pozzolanic activity with increasing water soluble fraction in the ashes tested. However, Joshi and Lam (9) have reported a strong correlation between soluble fraction and self cementing value of the ashes. It is quite possible the water soluble fraction is present as a thin coating on the fly ash particles and is highly reactive. The water soluble fraction reacts with the glassy material in the ash particles and produces cementitious compounds which in turn impart self cementing value to the ash. However, water soluble fraction does not seem to be related to the reactivity either with lime or cement.

Ash Fraction Of Different Specific Gravity

The data in Table 8 indicates that ash No. 13 contains significant amounts of particles which could be called cenospheres or floaters. It appears that ashes No. 1, 2, 6, 7, 8, 10, 12 and 13 contain significant amounts of particles of specific gravity between 1 and 1.45. All the particles of specific gravity less than 1.5 or even less than 2.0 have to have trapped gas bubbles, since all the glassy and crystalline matter in ash has a true specific gravity higher than 2.65. Visual observations indicated that the majority of the particles of specific gravity less than 2.0 could be easily discerned without the aid of any optical device. Therefore, the floaters apparently are present in the coarse fraction or the fraction retained on 45 μm meah sieve.

The presence of up to 2 weight percent or more of particles of

specific gravity 1.0 and 1.47 in ash No. 2, 7 and 13 makes them rich sources for lightweight fillers. Cenospheres of specific gravity < 1 present in excess of 1 percent can be economically recovered from the ash lagoons.

Magnetic Fraction

The magnetic fraction as reported in Table 2 represents the fraction or weight percent of ash particles attracted to a magnetic field. Majority of the ash particles are so small that they tend to get trapped between the magnetic particles during separation; as a result, it should be noted that the reported data include a large number of non-magnetic particles. Nevertheless, the data still clearly indicates large amounts of magnetic particles in ashes No. 9 through 14, which have high iron contents. The magnetic portion of these ashes may contain substantial amounts of magnetite rich particles which could possibly be used for coal refining. Mined magnetite is currently used to refine thermal coal.

CONCLUSIONS

Based on the laboratory test data of 14 Canadian ashes and literature search the following conclusions may be drawn:

1. The pozzolanic activity of the ashes tested seems to be related to the fraction retained on 45 μm mesh sieve, and surface area of an ash.
2. Of the 14 Canadian ashes investigated more than half seem to have potential for recovery of lightweight particles and cenospheres.
3. The ashes from Eastern Canada have relatively high amounts

of magnetic particles. These ashes could possibly be used as sources for magnetite for coal processing.

LIMITATIONS AND RECOMMENDATIONS

The results in this study are based on the tests conducted on samples as received from various plants. Fly ashes are known to vary in chemical and physical properties over the time. It is recommended that the ashes should be tested often to ensure the repeatability of results.

The subject of correlation between pozzolanic activity and ash properties should be investigated further. The basic properties such as glass content, strain in glass and form of the chemical constituent and surface characteristics of the ash particles should be studied in detail. Such a study may allow development of new and simple tests to evaluate pozzolanic activity of a fly ash.

ACKNOWLEDGEMENTS

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TABLE 1 - SOURCE OF 14 CANADIAN FLY ASHES

FLY ASH NO.	LOCATION OF POWER PLANT	TYPE OF COAL
1	Alberta	Sub-bituminous
2	Alberta	Sub-bituminous
3	Alberta	Sub-bituminous
4	Alberta	Sub-bituminous
5	Saskatchewan	Lignite
6	Saskatchewan	Sub-bituminous
7	Saskatchewan	Lignite
8	Saskatchewan	Lignite
9	Ontario	Bituminous
10	Ontario	Bitumnious
11	New Brunswick	Bituminous
12	New Brunswick	Bituminous
13	Nova Scotia	Bituminous
14	Nova Scotia	Bituminous

TABLE 2 - SUMMARY OF TEST DATA ON SOME PHYSICAL & CHEMICAL PROPERTIES OF 14 CANADIAN FLY ASHES.

FLY ASH NO. †	Coal Type	WEIGHT PERCENT ± 1σ											
		At as At_2O_3	Fe as Fe_2O_3	Ti as TiO_2	Ca as CaO	Mg as MgO	S as SO_3	Na as Na_2O	K as K_2O	Si as SiO_2	LOI**	Magnetic* Portion	Water Soluble Fraction
1	Sub-bitum.	22.3±0.5	4.1±0.1	1.01±0.01	13.6±0.4	1.58±0.04	0.2±0.1	0.27±0.03	1.02±0.06	54.8±0.4	0.16	≤1	1.22
2	Sub-bitum.	23.1±0.5	3.7±0.1	0.78±0.01	13.0±0.4	1.17±0.04	0.2±0.1	2.19±0.03	1.26±0.06	57.6±0.4	0.25	≤1	1.68
3	Sub-bitum.	21.0±0.5	3.5±0.1	0.50±0.01	11.6±0.4	0.71±0.04	≤0.1	1.68±0.03	1.51±0.06	56.4±0.4	0.75	≤1	1.74
4	Sub-bitum.	22.7±0.5	3.7±0.1	0.60±0.01	8.4±0.4	0.75±0.04	≤0.1	2.36±0.03	1.02±0.06	57.4±0.4	0.22	≤1	0.86
5	Lignite	23.7±0.5	4.4±0.1	0.94±0.01	19.2±0.4	3.96±0.04	0.6±0.1	0.54±0.03	2.41±0.06	57.9±0.4	0.22	≤1	3.03
6	Sub-bitum.	20.4±0.5	5.4±0.1	0.60±0.01	12.2±0.4	1.38±0.04	0.1±0.1	0.84±0.03	1.93±0.06	52.6±0.4	0.37	≤1	1.25
7	Lignite	20.8±0.5	4.1±0.1	0.97±0.01	20.0±0.4	3.13±0.04	0.2±0.1	5.66±0.07	1.14±0.06	40.7±0.4	2.5	≤1	1.97
8	Lignite	20.8±0.5	3.8±0.1	0.87±0.01	18.6±0.4	2.42±0.04	≤0.1	5.80±0.07	1.45±0.06	38.1±0.4	0.38	≤1	2.34
9	Bituminous	22.7±0.5	16.5±0.8	1.01±0.01	4.6±0.4	0.64±0.04	0.5±0.1	0.54±0.03	2.0±0.06	44.6±0.5	1.2	85.±1.	2.43
10	Bituminous	21.2±0.5	7.1±0.8	0.81±0.01	6.6±0.4	0.88±0.04	0.1±0.1	0.4±0.03	1.14±0.06	51.9±0.5	0.45	69.±1.	2.39
11	Bituminous	13.6±0.5	38.5±0.8	0.51±0.01	1.81±0.04	0.14±0.01	0.6±0.1	0.11±0.01	1.93±0.06	34.9±0.4	0.12	96.±1.	1.16
12	Bituminous	13.6±0.5	42.4±0.8	0.56±0.01	1.22±0.04	0.06±0.01	0.4±0.1	0.09±0.01	1.26±0.06	31.7±0.4	0.27	87.±1.	0.84
13	Bituminous	20.8±0.5	24.4±0.8	0.76±0.01	0.94±0.04	0.12±0.01	0.6±0.1	0.34±0.03	1.63±0.06	46.7±0.4	0.15	94.±1.	1.57
14	Bituminous	18.0±0.1	19.2±0.2	0.74±0.01	0.76±0.5	.75±0.04	.99±.05	.39±.03	2.93±.05	44.7±0.2	3.6		1.10

† See Table 1 for ash source.

* This is the amount of the sample attracted to a magnetic. It does not indicate the amount of magnetite.

** Loss on Ignition.

TABLE 3 - SPECIFIC SURFACE AREA OF 14 CANADIAN FLY ASHES

FLY ASH NO.	SPECIFIC SURFACE AREA*, cm^2/g
1	4150
2	4590
3	4280
4	5900
5	4990
6	2180
7	1740
8	2165
9	2800
10	2510
11	3100
12	1800
13	3570
14	3830

*As per ASTM C204 (Blaine Method).

TABLE 4 - DATA ON FRACTION, RETAINED ON 45 μm MESH SIEVE FOR 14 CANADIAN FLY ASHES.

FLY ASH NO.	PERCENT RETAINED ON 45 μm MESH SIEVE BY ALPINE SIEVE ANALYSIS
1	32.0
2	26.0
3	22.0
4	9.8
5	2.8
6	20.4
7	44.8
8	26.6
9	24.0
10	27.0
11	21.4
12	26.4
13	28.2
14	34.2

TABLE 5 - SPECIFIC GRAVITY OF
14 CANADIAN FLY ASHES

FLY ASH No.	SPECIFIC GRAVITY*
1	2.19
2	1.92
3	1.91
4	2.03
5	2.54
6	2.15
7	2.37
8	2.39
9	2.46
10	2.31
11	2.94
12	2.87
13	2.53
14	2.44

* Average of two sets.

TABLE 6 - POZZOLANIC ACTIVITY WITH PORTLAND CEMENT OF 14 CANADIAN FLY ASHES

FLY ASH NO.	COMPRESSIVE STRENGTH OF MORTAR WITH 35% REPLACEMENT OF CEMENT BY FLY ASH,* MPa	POZZOLANIC ACTIVITY INDEX WITH PORTLAND CEMENT, %
1	22.0	77.7
2	24.1	85.2
3	24.3	85.9
4	31.5	111.3
5	47.1	166.4
6	17.3	61.4
7	15.3	54.1
8	21.1	74.6
9	27.1	95.8
10	28.3	100.0
11	26.5	93.6
12	22.5	79.5
13	26.9	95.1
14	18.3	64.7

* As per ASTM C 311. Average of 3 samples.

TABLE 7 - POZZOLANIC ACTIVITY WITH LIME OF 14 CANADIAN FLY ASHES

FLY ASH NO.	POZZOLANIC ACTIVITY* WITH LIME	
	psi	MPa
1	1020	7.0
2	870	6.0
3	1040	7.2
4	1240	8.6
5	1885	13.0
6	745	5.1
7	465	3.2
8	795	5.5
9	1015	7.0
10	1000	6.9
11	925	6.4
12	555	3.8
13	935	6.5
14	735	5.1

* As per ASTM C 311.

TABLE 8 - DATA ON PARTICLES OF VARIOUS SPECIFIC GRAVITY IN 14 CANADIAN FLY ASHES

FLY ASH NO.	PERCENT FLOATERS* ON LIQUIDS OF DENSITY		
	1.47 g/cm^3	1.0 g/cm^3	0.78 g/cm^3
1	1.7 - 2.7	.5 - .65	.25 - .35
2	2.1 - 3.2	.45 - .55	.25 - .3
3	.7 - .8	.1 - 1.1	.07 - .09
4	.35 - .55	.2 - .22	.08 - .12
5	0.3 - 0.5	.2 - .23	.13 - .17
6	1.3 - 1.6	.3 - .6	.3 - .5
7	2.5 - 2.8	.5 - .75	.4 - .6
8	1.1 - 1.4	.6 - .8	.2 - .4
9	.8 - 1	.3 - .5	.1 - .3
10	1.2 - 1.5	.25 - .4	.2 - .3
11	.7 - .9	.2 - .5	.08 - .1
12	.8 - 1.2	.6 - .8	.3 - .5
13	1.8 - 2.4	1.1 - 1.4	.7 - .1
14	0.05 - 0.07	0.01 - 0.04	0.003 - 0.01

* Average of two sets.

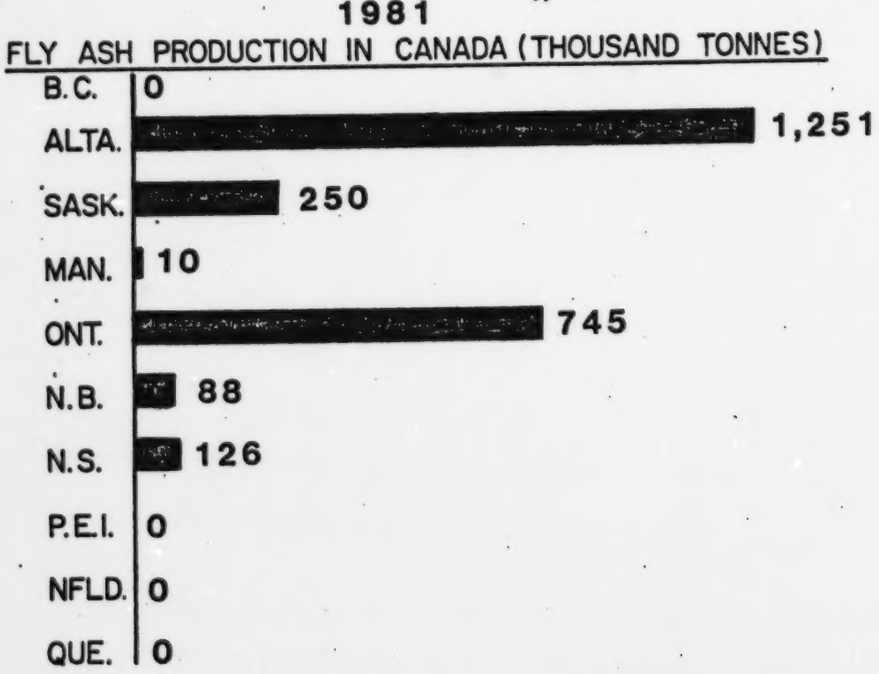

FIG. 1 LOCATIONS OF 14 POWER PLANTS AND 1981 FLY ASH PRODUCTION

From: Berry E.E., Heemings R.T. and Burns J.S., "Coal Ash in Canada, Ash as a Potential Resource" Vol. 1, Prepared for Canadian Electrical Association, Contract G195, March 1983.

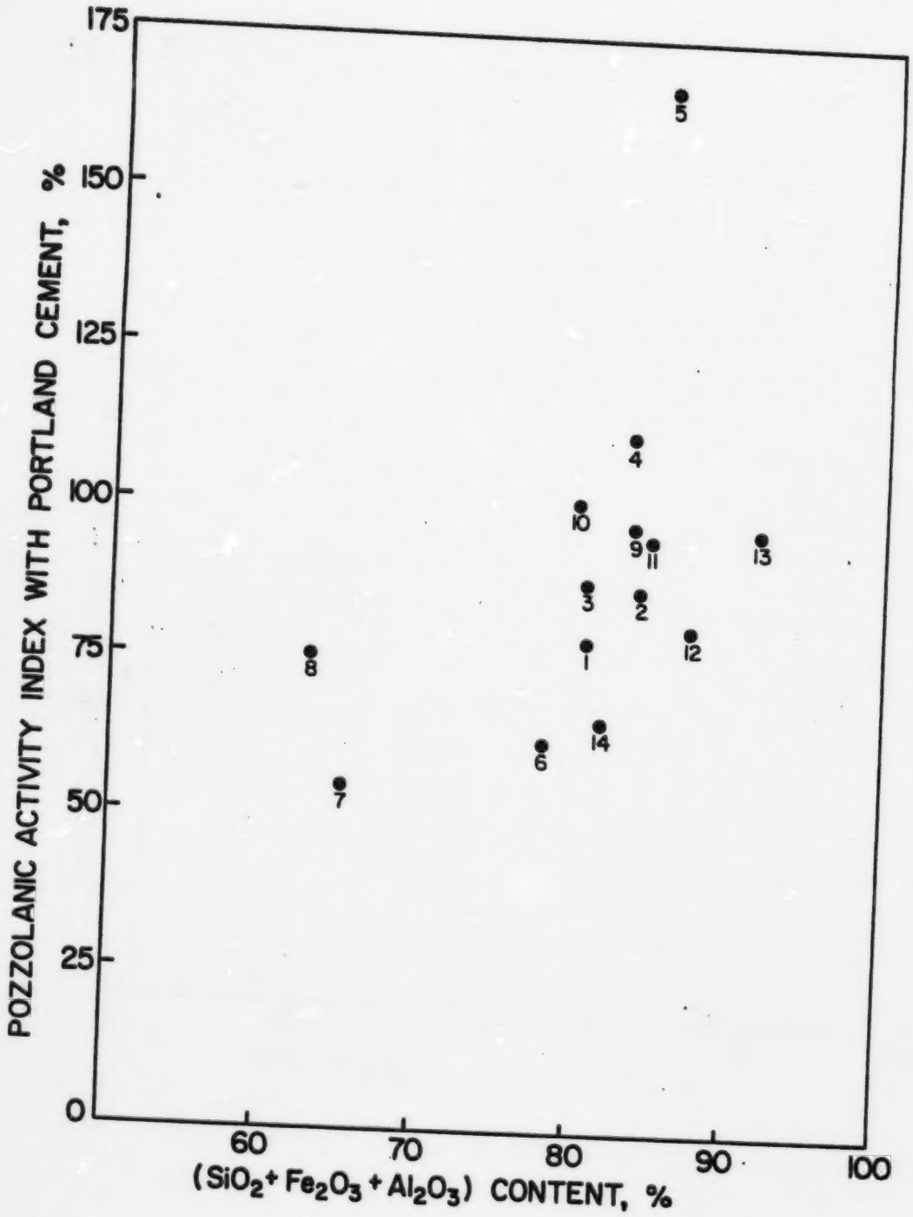

FIG. 2 (SiO_2 + Fe_2O_3 + Al_2O_3) CONTENT VERSUS POZZOLANIC ACTIVITY INDEX WITH PORTLAND CEMENT OF 14 CANADIAN FLY ASHES.

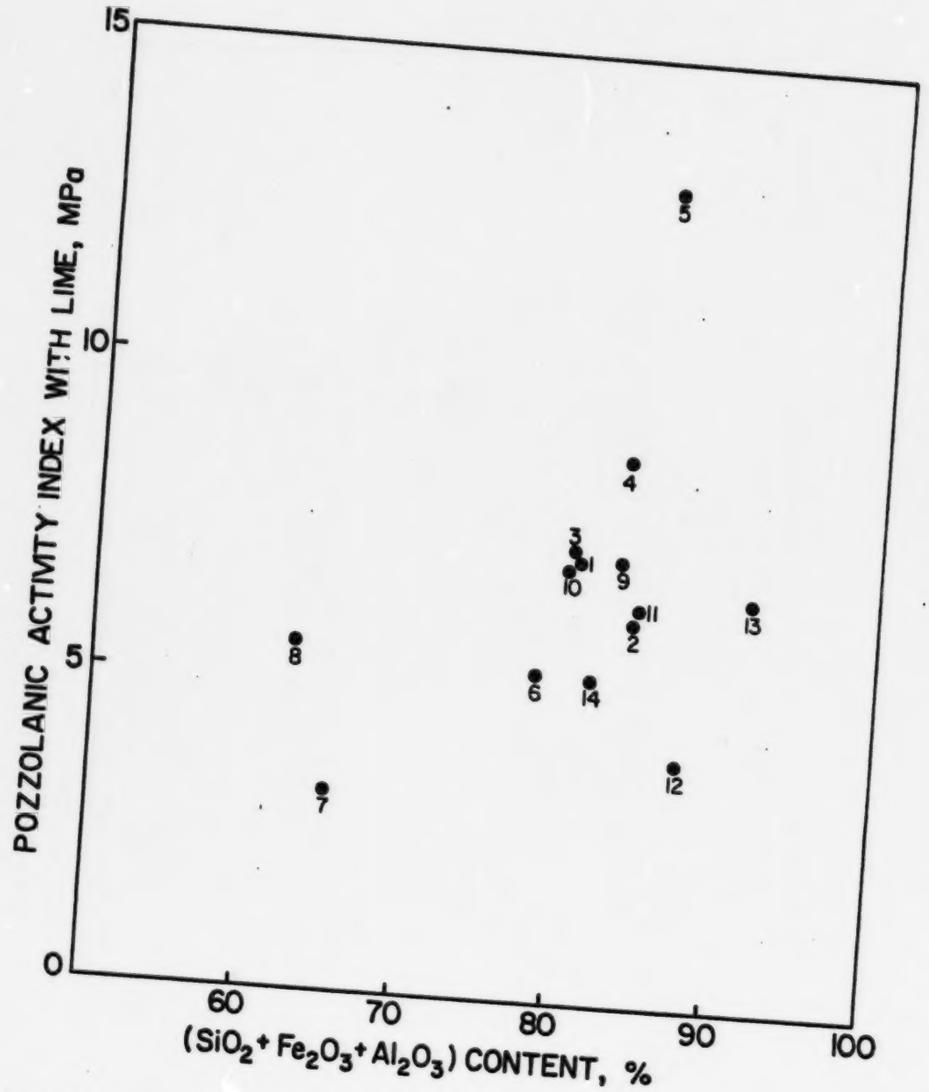

FIG. 3 (SiO_2 + Fe_2O_3 + Al_2O_3) CONTENT VERSUS POZZOLANIC ACTIVITY INDEX WITH LIME OF 14 CANADIAN FLY ASHES.

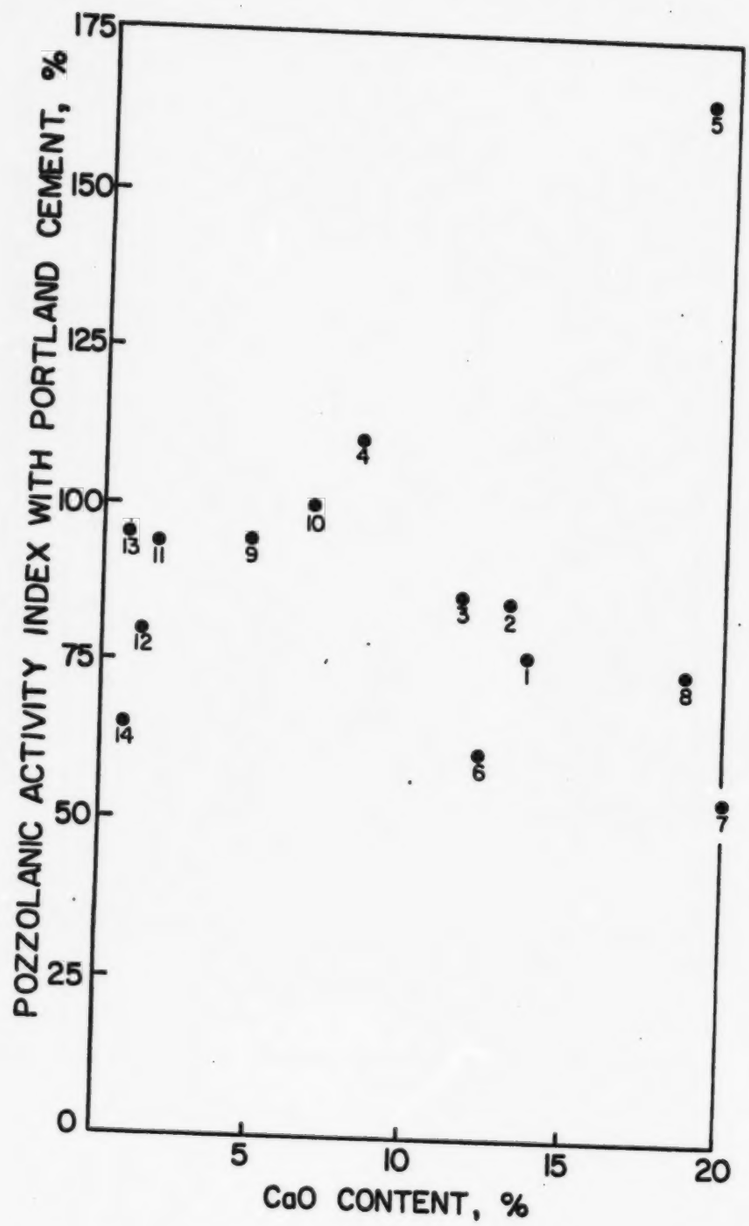

FIG. 4 CaO CONTENT VERSUS POZZOLANIC ACTIVITY INDEX WITH PORTLAND CEMENT OF 14 CANADIAN FLY ASHES.

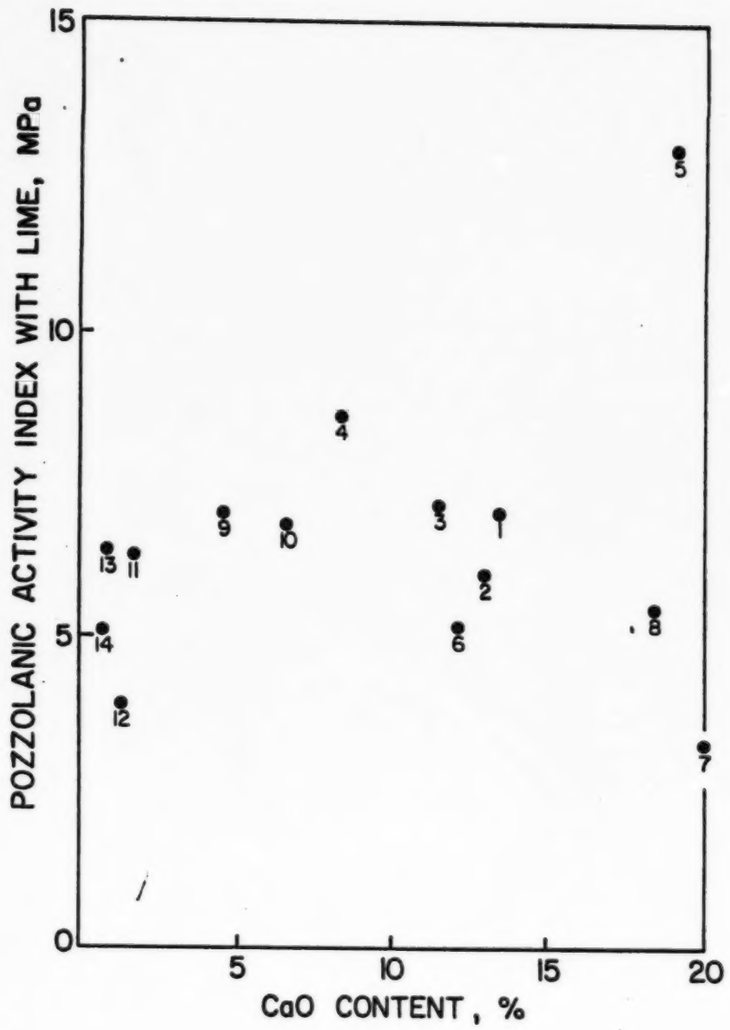

FIG. 5 CaO CONTENT VERSUS POZZOLANIC ACTIVITY INDEX WITH LIME OF 14 CANADIAN FLY ASHES.

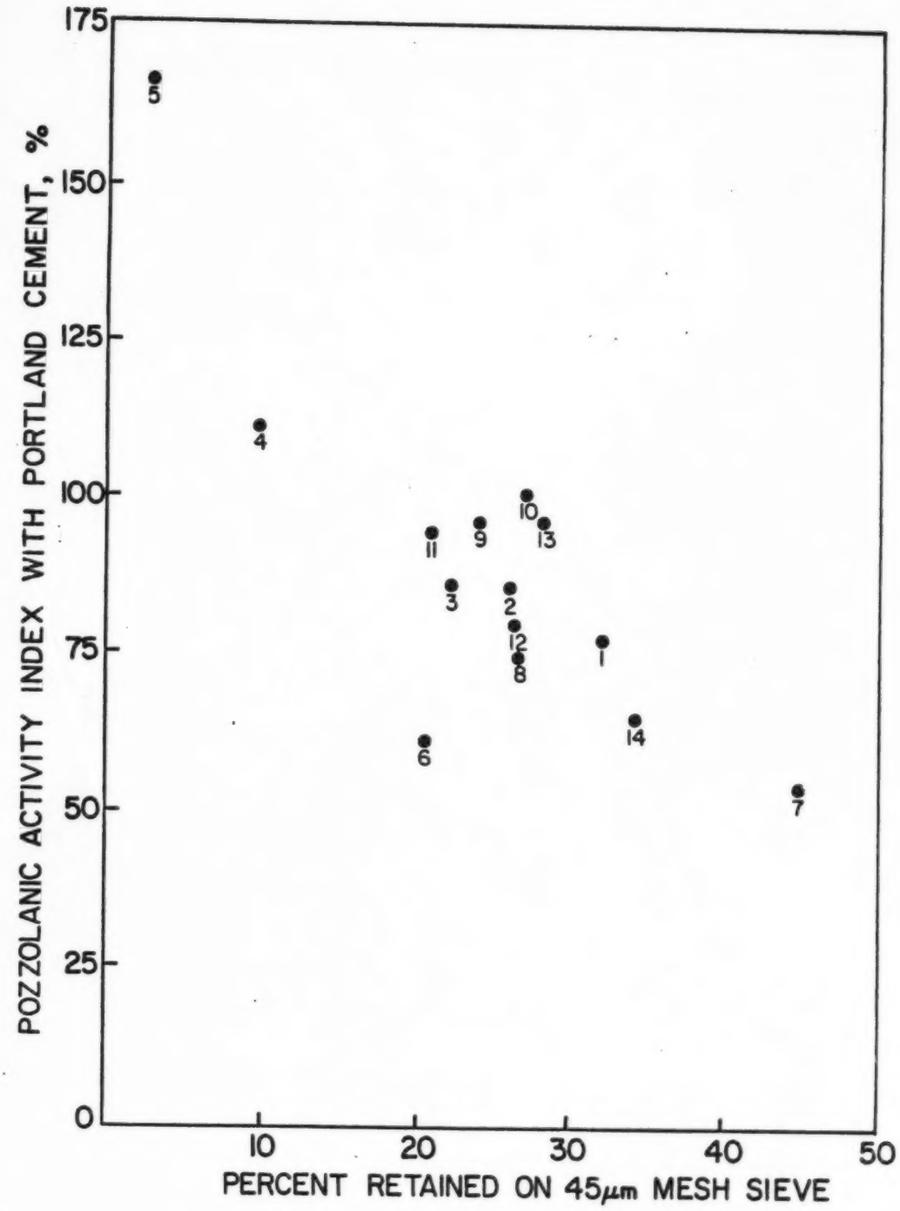

FIG. 6 PERCENT RETAINED ON 45 μm MESH SIEVE VERSUS POZZOLANIC ACTIVITY INDEX WITH PORTLAND CEMENT OF 14 CANADIAN FLY ASHES.

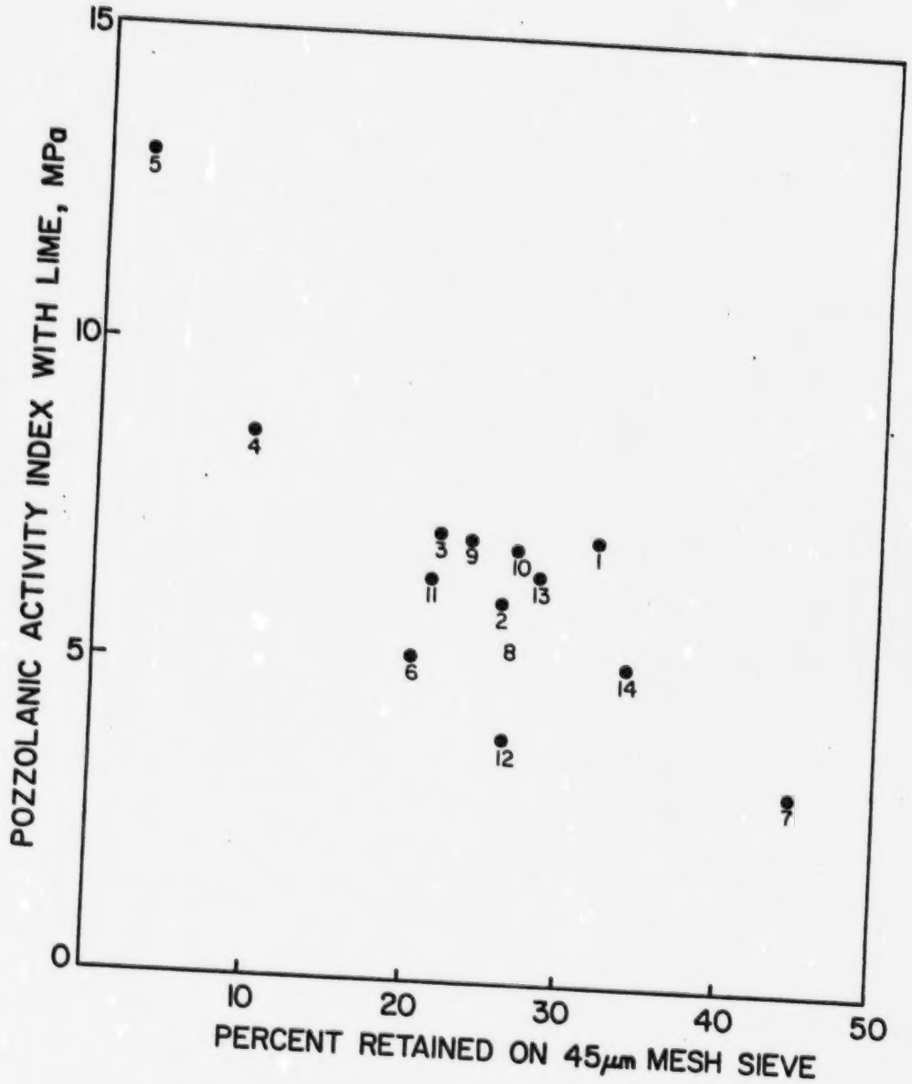

FIG. 7 PERCENT RETAINED ON 45 μm MESH SIEVE VERSUS POZZOLANIC ACTIVITY INDEX WITH LIME OF 14 CANADIAN FLY ASHES.

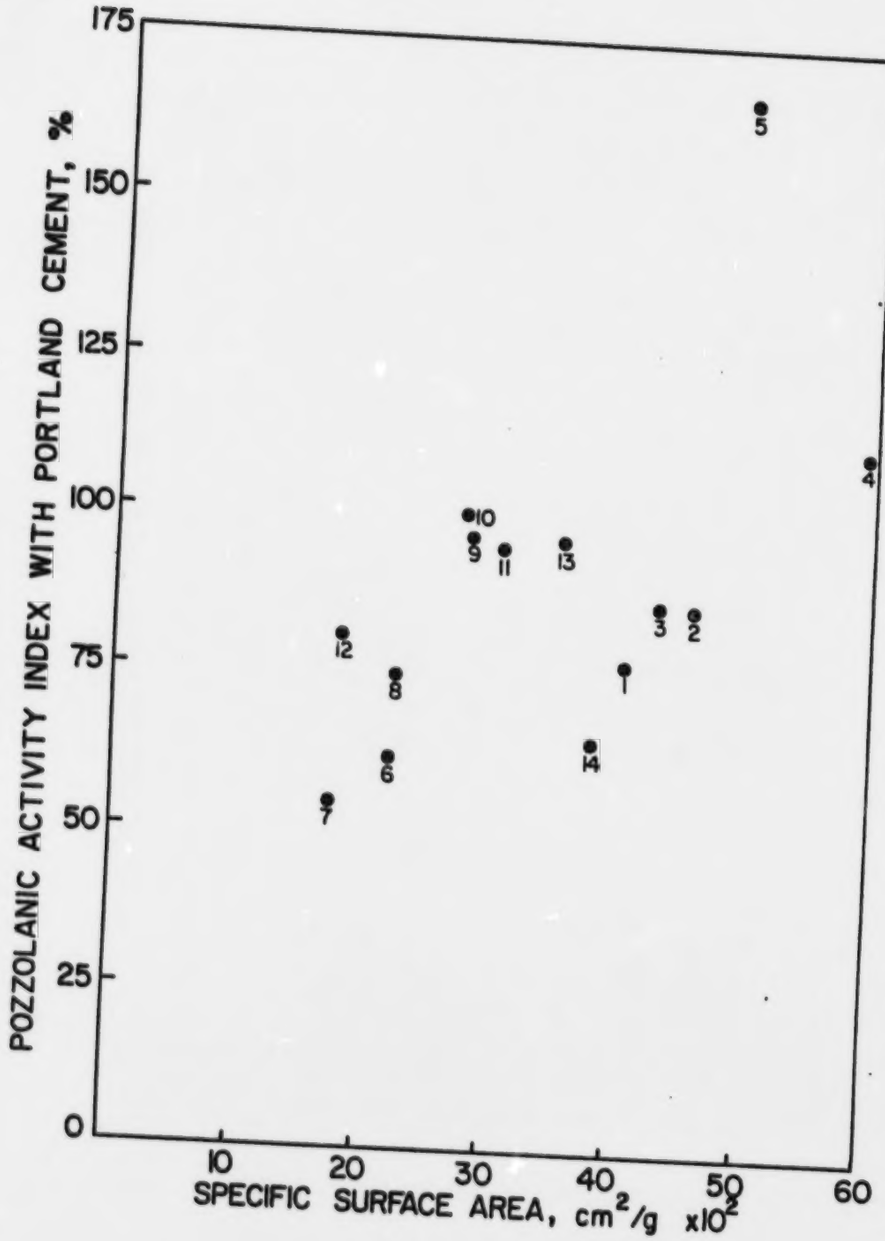

FIG. 8 SPECIFIC SURFACE AREA VERSUS POZZOLANIC ACTIVITY INDEX WITH PORTLAND CEMENT OF 14 CANADIAN FLY ASHES.

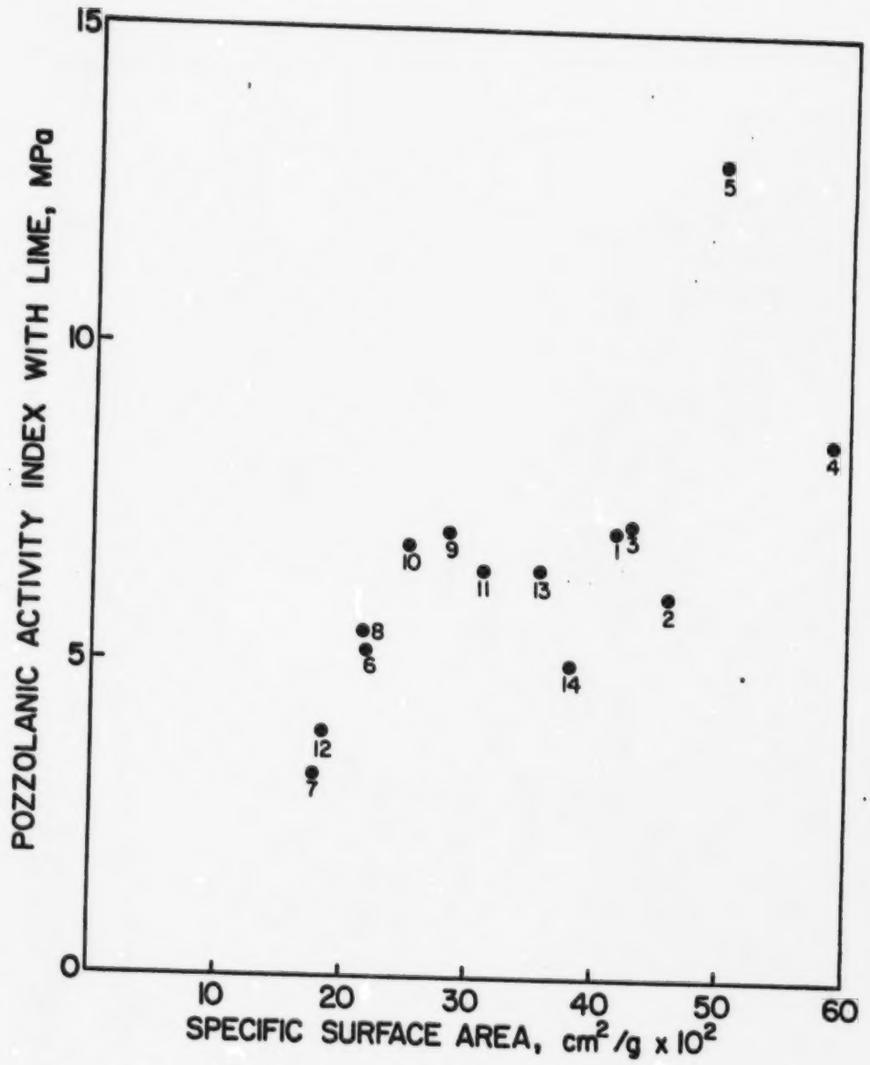

FIG. 9 SPECIFIC SURFACE AREAS VERSUS POZZOLANIC ACTIVITY INDEX WITH LIME OF 14 CANADIAN FLY ASHES.

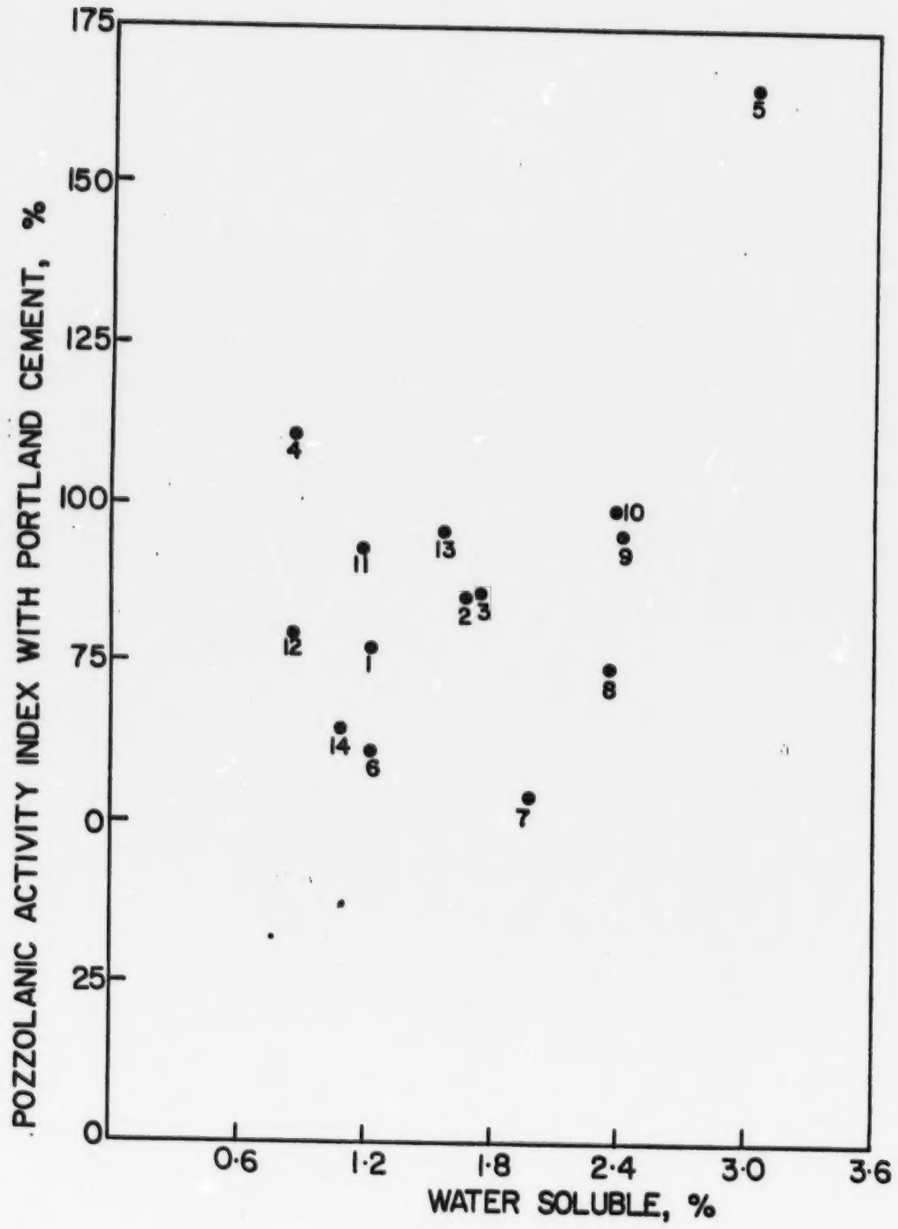

FIG. 10 WATER SOLUBLE FRACTION VERSUS POZZOLANIC ACTIVITY INDEX WITH PORTLAND CEMENT OF 14 CANADIAN FLY ASHES.

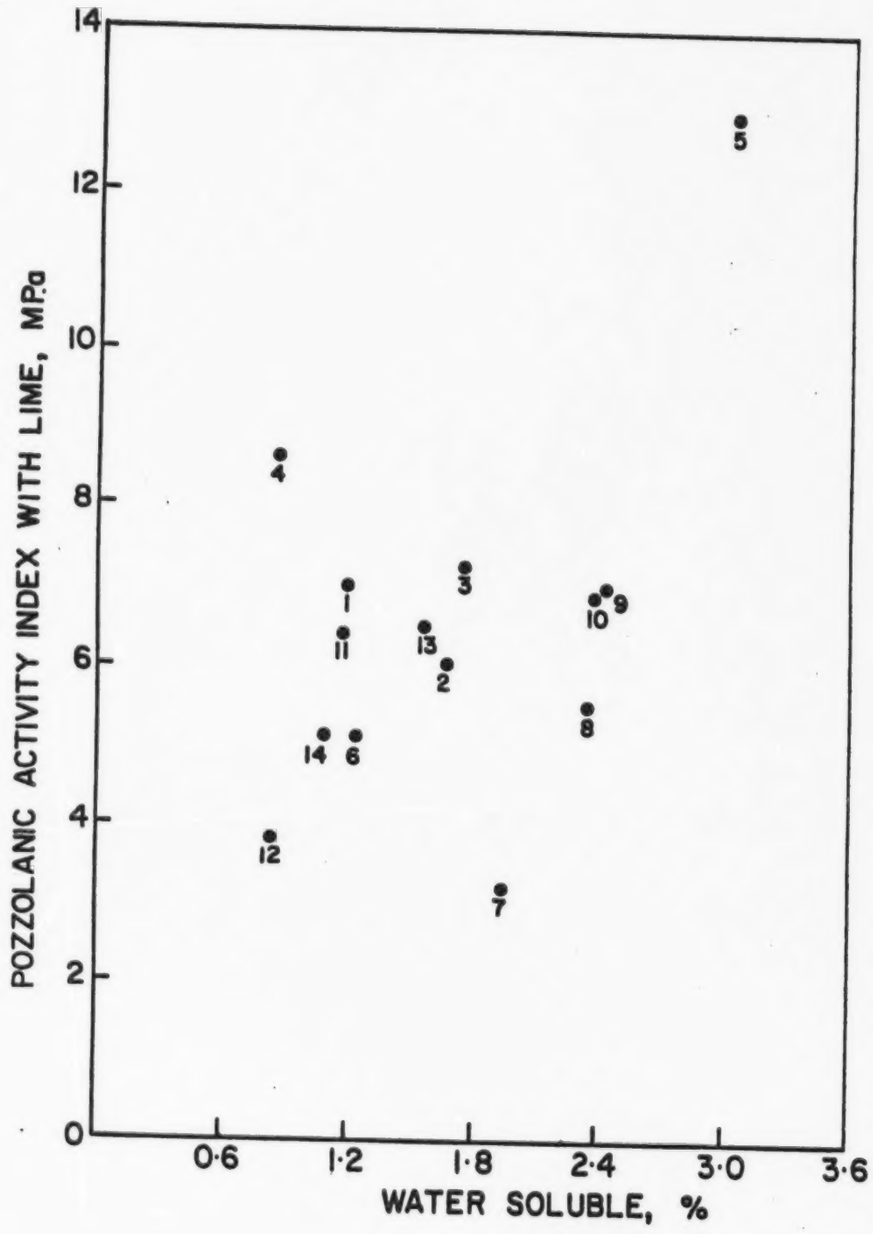

FIG. 11 WATER SOLUBLE FRACTION VERSUS POZZOLANIC ACTIVITY INDEX WITH LIME OF 14 CANADIAN FLY ASHES.

POOR

QUALITY

ORIGINAL